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Double-Layer Antireflection Coatings for CIGS Thin-Film Solar Cells

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Abstract.
Antireflection coatings are vital for reducing loss due to optical reflection in photovoltaic solar cells. A single-layer magnesium fluoride ($\mathrm{MgF_2}$) antireflection coating is usually used in thin-film CIGS solar cells. According to optics, this coating can be effective only for a narrow spectral regime. Further reduction of reflection loss may require an optimal single-layer or multi-layer coating. Hence, we optimized the refractive indices and thicknesses of single- and double-layer antireflection coatings for CIGS solar cells containing a CIGS absorber layer with: (i) homogeneous bandgap, (ii) linearly graded bandgap, or (iii) nonlinearly graded bandgap. A relative enhancement of up to 1.83% is predicted with an optimal double-layer antireflection coating compared to the efficiency with a single-layer antireflection coating.

Keywords: CIGS solar cells, antireflection coatings, optoelectronic optimization.

1 INTRODUCTION

Photovoltaic solar cells (PVSCs) are an eco-friendly source of energy of huge importance during the current climate emergency. Increasing the power conversion efficiency and thereby reducing the levelized cost of electricity generated by PVSC modules is essential to make PVSC technology globally competitive with conventional sources of energy and allow us to better tackle the climate emergency [1]. One way to enhance the efficiency is to reduce the reflection losses using an antireflection coating [2]. In thin-film CIGS solar cells, a single-layer coating of $\mathrm{MgF_2}$ is used to reduce the reflection loss. However, a single-layer antireflection coating can be effective only for a narrow spectral regime [2]. So, multi-layer antireflection coatings or graded-index antireflection structures are required to reduce the reflection loss over a broad spectral regime. But the graded-index antireflection structures such as moth-eye and nanowires structures [3] bring additional cost and complexity to the manufacturing process. In contrast, multi-layer antireflection coatings are easy to deposit using techniques such as thermal evaporation, reactive sputtering, and plasma-enhanced chemical vapor deposition. Hence, we optimized the refractive indices and thicknesses of single-layer and double-layer antireflection coatings for CIGS solar cells.

This paper is organized as follows. Optoelectronic modeling is discussed in Sec. 2. Numerical results are presented and discussed in Sec. 3, divided into two subsections. Section 3.1 provides the optimal results for solar cells with single-layer antireflection coatings. Optimal results for solar cells with double-layer antireflection coatings are presented in Sec. 3.2. The paper ends with conclusions in Sec. 4.

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2 OPTOELECTRONIC MODELING

The CIGS thin-film solar cell has the ARC/AZO/od-ZnO/CdS/CIGS/Al_2O_3/Mo structure [4] shown in Fig.1(a). The commonly used antireflection coating is made of magnesium fluoride (MgF_2) with a thickness of 110 nm. The thicknesses of the remaining layers are as follows: AZO 100 nm, oxygen-deficient ZnO 80 nm, CdS 70 nm, CIGS 2200 nm, Al_2O_3 20 nm, and Mo 500 nm. A rigorous optoelectronic model [4] was used to determine the effect of antireflection coatings on the power conversion efficiency (η), the short-circuit density (J_{sc}), the open-circuit voltage (V_{oc}), and the fill factor (FF) of the solar cell. These parameters were calculated for normally incident unpolarized solar radiation with AM1.5G spectrum. The optoelectronic model has two submodels: optical and electrical. In the optical submodel, the transfer matrix method [5] was used to determine the local electron-hole-pair generation rate. This variable was used as an input to the electrical submodel, wherein the transport of electrons and holes in the od-ZnO/CdS/CIGS region was considered using the 1D drift-diffusion model with the assumption of ideal ohmic front and back contacts. A hybridizable discontinuous Galerkin scheme [4] was used for the drift-diffusion equations. The Shockley–Read–Hall and radiative electron-hole recombination processes [4] were incorporated into the model. The differential evolution algorithm [6] was used to optimize the efficiency for single-layer and double-layer antireflection coatings [shown in Fig. 1(b)] for a CIGS absorber layer with: (i) a homogeneous bandgap, (ii) a linearly graded bandgap, or (iii) a nonlinearly graded bandgap. The thickness of the top layer in the double-layer antireflection coating is denoted by L_{ARC1}, the thickness of the second layer by L_{ARC2}, the refractive index of the top layer by n_1, and the refractive index of the second layer by n_2. Both $n_1 > 1$ and $n_2 > 1$ were taken to be independent of frequency.

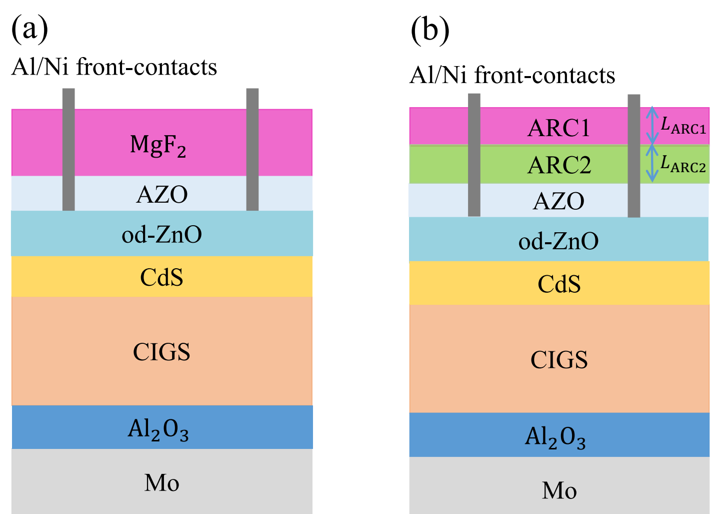

Fig. 1. Schematic of a CIGS thin-film solar cell with (a) a magnesium-fluoride antireflection coating, and (b) a double-layer antireflection coating.

3 RESULTS AND DISCUSSION

3.1 Single-layer antireflection coating

First, we considered the optimization of the solar cell with a single-layer antireflection coating ($L_{ARC2} = 0$). The parameter space for optimizing η was chosen as: $L_{ARC1} \in [0, 1000]$ nm and $n_1 \in [1, 2.2]$. For a homogeneous CIGS absorber layer, the maximum efficiency predicted is 18.39% and the optimal parameters are $n_1 = 1.4$ and $L_{ARC1} = 106$ nm. The corresponding values of J_{sc}, V_{oc}, and FF are 31.50 mA cm^{-2}, 700 mV, and 83%, respectively. For a linearly graded-bandgap

CIGS absorber layer, the maximum efficiency predicted is 24.11% and the corresponding values of $J_{\rm sc}$, $V_{\rm oc}$, and FF are 36.59 mA cm^{-2}, 810 mV, and 81%, respectively. For a nonlinearly graded-bandgap CIGS absorber layer, the maximum efficiency predicted is 30.02% and the corresponding values of $J_{\rm sc}$, $V_{\rm oc}$, and FF are 37.83 mA cm^{-2}, 990 mV, and 80%, respectively. The optimal refractive index and thickness of the antireflection layer remain the same for both graded-bandgap absorber layers as predicted for the homogeneous absorber layer. $\rm MgF_2$ has a refractive index of 1.39 in the considered spectral regime (300 nm–1200 nm), very close to the optimal value n_1, and this material is already used for CIGS solar cells.

3.2 Double-layer antireflection coating

Next, we considered the optimization of the solar cell with a double-layer antireflection coating. The parameter space for optimizing η was chosen as: $L_{\rm ARC1} \in [0, 1000]$ nm, $L_{\rm ARC2} \in [0, 1000]$ nm, $n_1 \in [1, 2.2]$, and $n_2 \in [1, 2.2]$. For a homogeneous CIGS absorber layer, the maximum efficiency predicted is 18.71% and optimal parameter are $n_1 = 1.28$, $n_2 = 1.74$, $L_{\rm ARC1} = 120$ nm, and $L_{\rm ARC2} = 76$ nm. The corresponding values of $J_{\rm sc}$, $V_{\rm oc}$, and FF are 32.05 mA cm^{-2}, 700 mV, and 83%, respectively. For a linearly graded-bandgap CIGS absorber layer, the maximum efficiency predicted is 24.54% and the corresponding values of $J_{\rm sc}$, $V_{\rm oc}$, and FF are 37.20 mA cm^{-2}, 810 mV, and 81%, respectively. For a nonlinearly graded-bandgap CIGS absorber layer, the maximum efficiency predicted is 30.57% and the corresponding values of $J_{\rm sc}$, $V_{\rm oc}$, and FF are 38.47 mA cm^{-2}, 990 mV, and 80%, respectively. The optimal refractive indices and thicknesss of both layers in the antireflection coating remain the same for both graded-bandgap absorber layers as predicted for the homogeneous absorber layer.

4 CONCLUSIONS

Thus, an enhancement of up to 1.83% is predicted in the efficiency with an optimal double-layer antireflection coating relative to the efficiency with a single-layer antireflection coating. Adoption of the double-layer configuration over the single-layer configuration may not be economically viable.

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